

Simulations of tidally induced spiral arms

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The origin of grand design spiral structure in galaxies is still under debate but one of promising scenarios involves tidal interactions. We use N -body simulations to study the evolution of a Milky Way-size galaxy in a Virgo-like cluster. The galaxy is placed on a typical eccentric orbit and evolved for 10 Gyr. We find that grand design spiral arms are triggered by pericenter passages and later on they wind up and dissipate. The arms formed in the simulations are approximately logarithmic, but are also dynamic, transient and recurrent.

1 Introduction

Formation and evolution of spiral arms in galaxies remains one of the great unsolved problems in modern astrophysics. Several theories aim to explain this phenomenon, but none of them is generally believed to be complete and universally applicable. One of the scenarios proposes that spiral arms originate from tidal interactions with another body, e.g. a galaxy of similar size. This idea was first explored in the seminal paper by Holmberg (1941).

More recent studies using full N -body simulations (e.g. Oh et al., 2015) support the hypothesis that tidal encounters induce grand design, two-armed spiral structure (as seen e.g. in M51). Oh et al. (2015) discussed the results of N -body simulations of the satellite triggering the formation of spiral arms in a larger, disk galaxy. They found the arms to be approximately logarithmic in shape and decaying with time.

In this paper we present first results of N -body simulations of a Milky Way-size galaxy orbiting in the Virgo-like cluster. We find that the formation of grand design spiral arms in a galaxy can be triggered by tidal interactions with the cluster-size dark matter halo.

2 The simulations

In our simulations the galaxy was modelled as an exponential stellar disk embedded in an NFW (Navarro et al. 1997) dark matter halo. The model had properties similar to the Milky Way model MWb of Widrow & Dubinski (2005). The dark matter halo had a virial mass $M_H = 7.7 \times 10^{11} M_\odot$ and concentration $c = 27$. The disk had a mass $M_D = 3.4 \times 10^{10} M_\odot$, the scale-length $R_D = 2.82$ kpc and thickness $z_D = 0.44$ kpc. The initial conditions fulfilled the Toomre's stability criterion ($Q > 2$).

The Virgo cluster was approximated as an NFW dark matter halo with parameters estimated by McLaughlin (1999) and Comerford & Natarajan (2007), namely the virial mass $M_C = 5.4 \times 10^{14} M_\odot$ and concentration $c = 3.8$. The N -body realizations for both, the galaxy and the cluster, were generated via procedures described in Widrow & Dubinski (2005) and consisted of 10^6 particles per component.

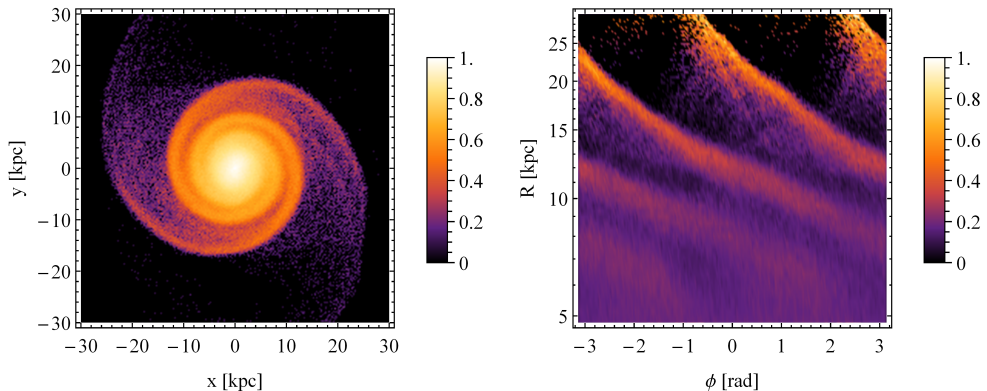


Fig. 1: *Left*: Face-on view of the surface density distribution of stars in the disk at 2.75 Gyr. The color bar labels were normalized to $0.32 \log[1 + \Sigma / (3.76 \times 10^5 M_\odot / \text{kpc}^2)]$. *Right*: Perturbed surface density at the same time in the $\phi - \ln R$ plane. The color bar labels were normalized to $0.53 \log[2 + (\Sigma - \Sigma_0) / \Sigma_0]$.

The galaxy was placed at an apocenter of a typical eccentric orbit in the Virgo cluster with an apo- to pericenter distance ratio of $r_{\text{apo}}/r_{\text{peri}} = 1500/300$ kpc. The evolution was followed for 10 Gyr with the GADGET-2 N -body code (Springel 2005).

3 Evolution and structure of spiral arms

Grand design, two-armed structures form after the first pericenter passage of the galaxy on its orbit in the Virgo cluster. The left panel of Fig. 1 shows the face-on view of the surface density of the disk at 2.75 Gyr, i.e. 0.85 Gyr after the first pericenter. The right panel of the Figure shows the perturbed density $(\Sigma - \Sigma_0)/\Sigma_0$ (where Σ is the surface density at a given time and Σ_0 is the initial value) at the same time in the $\phi - \ln R$ plane. The right-panel plot demonstrates that the spiral arms are approximately logarithmic.

The spiral structure formed shortly after the pericenter passage is not stable, but the arms wind up with time. After about 2 Gyr they dissolve to be triggered again during the next pericenter passage. This recurrent, transient behaviour is confirmed by the measurements of the pitch angle and the arm strength.

We expanded the surface distribution of stars in the ring $9 \text{ kpc} \leq R \leq 15 \text{ kpc}$ in logarithmic spirals according to the formula $A(p) = (1/N_s) \Sigma_j \exp[i(2\phi_j + p \ln R_j)]$ where N_s is the number of stars and (ϕ_j, R_j) are the coordinates of the j th star (see e.g. Sellwood & Athanassoula, 1986). We then find p_{max} that maximizes $|A(p)|$ and the pitch angle α from $\tan \alpha = 2/p_{\text{max}}$. The measurements are shown as a function of time with the red line in Fig. 3. Just after the pericenters, when the arms form, α is as high as $\sim 35^\circ$ and then it exponentially decreases to $\sim 5^\circ$. This decrease of pitch angle corresponds to the arms winding up during the evolution.

The Figure also shows the arm strength $|A(p_{\text{max}})|$ as a function of time with the dashed blue line. The arm strength clearly rises during and just after pericenters and then decreases. This means that arms are dissolving but they do not entirely vanish before the next pericenter.

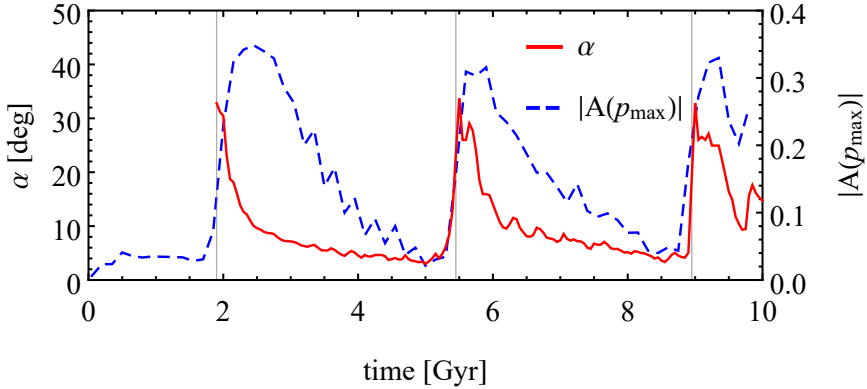


Fig. 2: The evolution of the pitch angle α and the arm strength $|A(p_{\max})|$ measured in the ring of $9 \text{ kpc} \leq R \leq 15 \text{ kpc}$. Gray vertical lines indicate pericenter passages.

4 Summary

We performed N -body simulations of a Milky Way-like galaxy orbiting in a Virgo-like cluster. We found that tidal forces from the cluster induce the formation of grand-design spiral arms at pericenter passages. The spiral arms wind up and weaken with time until the next pericenter when they are recreated.

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